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Project DUSTORM Report: Ozone Measurements and Meteorological Analyses of Tropopause Folding

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Project DUSTORM Report: Ozone Measurements and Meteorological Analyses of Tropopause Folding+

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Vertical profiles of ozone mixing ratio, averaged to remove the fluctuations, are consistent with a net production in the upper stratosphere and a net destruction at the earth's surface. The mean mixing ratios decrease downward by more than two orders of magnitude, but the gradient is not uniform. Most of the gradient is concentrated in the lower stratosphere, from 25 km down to the tropopause. This region is, in effect, a transition region between the dynamically active troposphere and the chemically active stratosphere. Its mean circulations and wave motions are strongly forced by and coupled with those in the troposphere. The coupling leads to a direct mass exchange, transporting ozone, radioactivity and potential vorticity from the lower stratosphere into the troposphere.

Transport occurs when the boundary between the stratosphere and the troposphere deforms, becomes vertical in the core of the jet stream, and then folds beneath the jet core. Reed and Danielsen (1959) showed that the folded structure could be identified by its large values (stratospheric values) of potential vorticity and used the term "tropopause folding" to describe the process.

After completing several case studies of large-scale cyclogenesis in which the three-dimensional trajectories were determined from isentropic analyses, and the associated mass transports from the stratosphere were computed, Danielsen (1959) concluded that tropopause folding was an

integral part of cyclogenesis and that, therefore, the net seasonal and annual transport of mass could be estimated by multiplying the mass transport per cyclogenesis times the number of cyclogenetic events. His estimate of 4.3×10^{20} gm year^{-1} implied that a mass comparable to the entire Northern Hemispheric stratosphere was exchanged in one year, the outflow being from the lower stratosphere on the cyclonic side of the jets, the inflow implied at higher elevations on the anticyclonic side of the jets.

An obvious implication of the above estimate is that radioactivity injected or produced in the stratosphere will be rapidly transported into the troposphere whenever it reaches the lower stratosphere. To prove that bomb debris is so transported by the tropopause folding phenomenon, Danielsen organized and directed Project Springfield in April 1963. In this multi-aircraft experiment the phenomenon was predicted, and aircraft equipped to measure radioactivity were vectored to intersect the predicted, folded structure. The results (Danielsen, 1964; 1968) confirm the hypothesis.

Another obvious implication of the stratospheric-tropospheric exchange is that ozone is rapidly removed from the lower stratosphere, and that the seasonal and annual removal rates can be estimated if the mean mixing ratio is determined in the outflowing air. On the basis of strontium-90 concentrations measured in the lower stratosphere in 1960 and 1963, and monthly deposition of Sr-90

at the surface, Danielsen has deduced a mass outflow rate from the stratosphere,

$$\frac{dM}{dt}_{outflow} = \left[3.6 + 1.8 \cos \frac{2\pi}{\tau}\left(t - \frac{4.5}{12}\right)\right] \times 10^{20} \text{ gm yr}^{-1} \qquad (1)$$

where τ = 1 year and τ varies from 0 to 1 year.

The maximum outflow in mid-April is 3 times the minimum in mid-October and the annual outflow is about 80% of the total Northern Hemisphere's stratospheric mass.

A similar expression for the ozone mass mixing ratio in the lower stratosphere,

$$\chi_m = \left[1.3 + 0.3 \cos \frac{2\pi}{\tau}\left(t - \frac{4.5}{12}\right)\right] \times 10^{-6} \text{ gm/gm} \qquad (2)$$

was derived from ozonesonde data (Hering and Borden, 1964). These magnitudes also agree with those derived by Danielsen from the positive correlation between radioactivity, potential vorticity and ozone.

The product of (1) and (2) predicts an annual outflow of 4.7×10^{14} gm of O_3 or 5.8×10^{36} molecules. This value corresponds to an average vertical flux of 7×10^{10} molecules $cm^{-2} sec^{-1}$ for the Northern Hemisphere, falling between the 4×10^{10} estimated by Paetzold (1955) and the $14 \pm 2) \times 10^{10}$ computed at O'Neill, Nebraska by Regener (1957). It is close to the upper limit of 7.6×10^{10} molecules $cm^{-2} sec^{-1}$ estimated by Fabian and Junge (1970) and 1.7 times their lower limit.

Also, from the product of (1) and (2), one can show that the ozone injected into the troposphere in late spring is

approximately 5 times that injected during the late fall. Observations of near surface ozone show a comparable trend. For example, the late spring maximum at Boston is 5 times the late fall minimum. This trend could survive even with a local production by ultraviolet light and hydrocarbons if the production is proportional to the amount of ozone present.

When converted from mass to number mixing ratio the limits implied by (2) are 600 to 1000 ppb, i.e., 8 to 12 times the 80 ppb specified by the Environmental Protection Agency as an upper limit in air if it extends over an hour. The ozone extruded in the folded tropopause, therefore, has the potential for exceeding the EPA standard. To what extent it will exceed the standard depends upon the dilution caused by mixing during the air's descent. Measurements of radioactivity made in Project Springfield show that the dilution is concentrated along both the upper and lower boundaries, i.e., the zone or layer is maintained by a convergent inflow normal to the boundaries which counteracts the turbulent diffusion. In the center the dilution is usually less than a factor of 3 to 5. Therefore, if the layer descends close to the ground the EPA standard can be exceeded.

Data from three examples of tropopause folding will now be presented which demonstrate the potential. The measurements were made in Project DUSTORM during April 1975. Large-scale cyclogenesis was predicted to study the effects of soil-generated aerosols on severe convective storms. Be-

cause the extruded stratospheric air is entrained into the developing cumulonimbus clouds, a comprehensive set of measurements were made aboard the Electra aircraft in the folded structure. Ozone was measured by two sensors - a potassium iodide sensor supplied by the Aerosol Project of the National Center for Atmospheric Research (NCAR), and an ethylene chemiluminescent sensor supplied by the Atmospheric Science Research Center of the State University of New York at Albany (SUNYA). Because these sensors cannot operate against a large pressure differential they were connected to the compressed air entering the cabin. An ozone loss is, therefore, unavoidable and the values presented are estimated to be about 70% of the environmental values.

The Electra flights were made between 21,000 and 25,000 ft. (6.3 to 7 km). The aircraft first traversed the folded tropopause at the lower altitude, flying perpendicular to the wind. After the limits of the zone were determined, the plane turned back and re-entered the zone. Three upwind-downwind sampling flights were made - one near the warm boundary, one in the center and one near the cold boundary. Then the aircraft ascended and this flight pattern was repeated.

On the same day, but not simultaneously, V. Mohnen of SUNYA traversed the same storm system on a commercial aircraft, making ozone measurements at approximately 39,000-41,000 ft. (11.9 to 12.5 km). These data will also be pre-

sented and compared to the lower level flight data.

Case I - 18 April 1975

The first flight was directed southeastward from Denver toward Oklahoma City. Flying toward the trough, the Electra approached the layer of stratospheric air from the cold boundary side. Observed winds and height contours at 0000 GMT, 19 April, are shown in Fig 1. Asymmetry characterizes the contour gradients and the observed wind speeds, with velocities of 150 kts, 75 m sec^{-1} from the southwest at Oklahoma City. The red overlay delineates the intense potential temperature gradients in the folded tropopause zone and the extreme asymmetry that always typifies a horizontal cross-section of the zone. It extends from Los Angeles, California to Green Bay, Wisconsin over 3,000 km, but is only 220 km wide.

Figure 2 shows the vertical cross-section along the flight paths drawn from the radiosonde data. Isotherms of potential temperature drawn at a 2.5°K interval are tightly spaced in the sloping hyper-baroclinic zone. The red overlay depicts the isotachs and the boundary of the folded tropopause (dashed lines). This boundary is vertical through the jet core, separating cyclonic from anticyclonic relative vorticity on the isentropic surfaces.

Figures 1 and 2 were analysed from only the radiosonde data, but the agreement with the Electra aircraft data is

excellent. Profiles of temperature and wind speed measured during the first traverse at 443 mb, ~21,000 ft. or 6.4 km, are presented in Fig 3, which also delineates the cold and warm boundaries. The cold boundary is well defined by a rapid change in the temperature and wind speed gradients. The warm boundary is much less evident, being complicated by large amplitude perturbations about the mean. The periods of these perturbations measured by the aircraft vary from 1 to 6 min, which corresponds to wavelengths of about 9 to 54 km. These waves cannot be resolved by the radiosonde data, so low-pass, Fourier filters will be designed to eliminate them. The filtered data will then be compared to the radiosonde data.

The ozone and dew point profiles (red overlay of Fig 3) are effectively filtered by the sensors themselves. The ozone profile is from the potassium iodide sensor, which cannot respond to the short period wave perturbations. It also has a significant delay, > 3 min, when the ozone is decreasing, so the profile from the maximum at 2057 GMT to the warm boundary has been adjusted to agree with the profile measured on the return flight across the warm boundary. Data from the ethylene sensor is not shown. The sensor operated for only short periods because the ethylene level was too low. However, data obtained when the sensor was operating will be useful for evaluating the wave perturbations.

In general, there is excellent agreement between the temperature, wind speed, ozone and dew point profiles. In all profiles the gradients are a maximum near the cold boundary and are much smaller near the warm boundary. In agreement with the circulations proposed by Danielsen (1968) the ascending motion in the cold air leads to saturated or near saturated moist air being entrained along the cold boundary, while the descending motion along the warm boundary leads to the entrainment of relatively dry air. Note that the driest air correlates with the ozone rich air from the stratosphere.

The maximum ozone measured on the first traverse was 225 ppb. During the sampling missions at the same level (443 mb) a similar maximum was observed. The maximums measured during the ascent and during the sampling at 388 mb are still undetermined due to the hysteresis of the potassium iodide sensor and the low ethylene levels in the other sensor. After the complete data from Project DUSTORM are processed the response characteristics of the potassium iodide sensor will be determined by comparison with the ehtylene data, and adjusted values will be obtained.

The ozone profile obtained from the commercial flight is shown in Fig 3b. Between Boston Massachusetts and Buffalo, New York the plane was in the troposphere at 238 mb. After the ascent to 197 mb, the flight to California was entirely in the stratosphere.

The large-scale variations, including a minimum over Michigan, a maximum over South Dakota and another minimum over Nevada, correspond to the large-scale ridge/trough/ridge pattern shown in Fig 1. The maximum values, 450 $\pm$ 50 ppb, are twice those measured at 444 mb by the Electra. The maximum values are also positively correlated with the warmest temperatures, highest values of potential temperature encountered.

The small-scale minimums correlate with narrow regions of anticyclonic shear where the stability is sufficiently large to be considered as stratospheric, but the small absolute vorticity makes the potential vorticity as small as those in the troposphere. More comprehensive analyses on isentropic surfaces are necessary to determine the tropospheric origin of this air. Similar low values of potential vorticity associated with anticyclonic shears in the stratosphere can be seen in Fig 4 of Danielsen's 1968 paper. No radioactivity measurements were made in these regions, so the proof of its tropospheric characteristics were unconfirmed.

Case II - 26 April 1975

On the 26th the Electra was flown westward from Denver to approach a folded tropopause from the warm boundary side. The Montgomery stream function analysis and the observed winds on the 320 K isentropic surface are shown in Fig 4.

Air with stratospheric values of potential vorticity are shaded. The Electra flew through the jet near the Colorado-Utah border and then proceeded past Salt Lake City, through the trough, into the northerly flow over eastern Nevada. The commercial flight, traveling southwestward from Chicago, crossed the same trough at higher elevations between 1200 and 1330 GMT on the 26th. During this period the trough and jet moved slowly eastward and then retrogressed, so no substantial displacement is involved.

The vertical cross-section, Fig 5, indicates a typical pattern of isentropes and isotachs for a narrow, intense trough. At the Electra flight levels, the isentropes are domed, with highest elevations in the trough. At the commercial aircraft level, 210 mb (39,000 ft.; 11.5 km) the isentropes are domed at the tropopause (the wind maximum) and have their lowest elevations in the trough.

Observations from the return flight of the Electra at 7.7 km (373 mb) are profiled in Fig 6. The wind speed profile is a classic. Speeds increase parabolically from 15 m sec^{-1} in the trough to 68 m sec^{-1} at the jet, then decrease quasi-linearly in the tropospheric air. A spectrum of waves complicates the potential temperature profile, but if one visualizes a smooth, filtered curve a similar trend is evident. An increase in potential temperature, from 311 to 317 K, is indicated by the cross-section, which agrees with a smoothed profile in the stratospheric air.

However, in the troposphere, over the mountains, the flight data show potential temperatures that are 4^0 to 6^0 cooler than those in the cross-section. This deviation, plus the large fluctuations, suggests gravity wave modification caused by the mountains.

The ozone profile from the ethylene sensor is anti-correlated with the large-scale features since the stratospheric air is cooler here than the tropospheric air, but it is positively correlated with most of the wave perturbations. Maximum values at this level were 320 ppb with a very rapid decrease near the warm boundary. The profile measured from the commercial flight, Fig 6b, is approximately Gaussian between the two jets with a maximum of 500 ppb. It is positively correlated with the large-scale potential temperature pattern which increases from 335^0 at the jet boundaries to 355 K in the trough.

If the maximum of 500 ppb at a potential temperature of 355 K is compared to the 320 ppb measured aboard the Electra at 313 K, the gradient is 43 ppb $(^0K)^{-1}$. Extrapolating the same gradient down to the coldest stratospheric potential temperatures implies 265 ppb at 300 K. The largest values measured at 300 K were 180 ppb, implying a more effective dilution in the folded structure, which is logical due to the close proximity of the tropospheric boundaries. Tropospheric air is entrained and mixed along both boundaries. Despite this dilution, the values of 250 to 320 ppb measured

at potential temperatures from 308 to 313 K, the 180 to 250 ppb measured from 300 to 308 K, and the fact that these potential temperature surfaces intersect the ground in western Colorado implies the possibility that surface ozone values could exceed the EPA standard.

Case III - 27 April 1975

A new cyclone was predicted to form over Colorado during the 27th, and aircraft were dispatched to Texas and Oklahoma on the 25th and 26th for a major DUSTORM experiment. These aircraft operated during the afternoon of the 27th, when the Electra was sent south-southeast to detect evidence of stratospheric air. Figure 7 depicts the changes that occurred in the jet structure between the 26th and 27th. Air in the main jet over Utah, moving at speeds of 60-65 m sec^{-1} continued northward and turned anticyclonically over southern Canada. But, as indicated by the dashed line, some of the slower moving air closer to the trough was turned cyclonically by the eastward propagating pressure pattern, and then accelerated across northern Arizona and New Mexico. The low tropopause, from 300 to 305 K, potential temperature was also advected over Colorado.

When the Electra ascended south of Denver to 444 mb (21,000 ft.; 6.4 km) it intersected this low tropopause at 475 mb where the potential temperature was 305 K. The ozone increased from low values, 30 to 50 ppb in the tropo-

sphere, to 150-200 ppb. Flying southward the Electra passed over the coldest tropopause (300 K) near the Colorado-New Mexico border. The aircraft then flew several upwind-downwind sampling patterns on the cyclonic and anticyclonic sides of the jet. A secondary jet was intersected over the Texas panhandle after which the aircraft encountered dust. Danielsen directed the aircraft to ascend to 23,000 ft (7 km; 407 mb) where they entered clean air. The heavy dust stirred up to the 6.5 km level can be seen on the satellite visual photographs.

The vertical cross-section, Fig 8, is drawn from the 0000 GMT 28 April radiosonde data (four hours after the flight path sketched in Fig 7) when the Electra was returning to Denver. During these four hours the tropopause was raised by ascending moist air to about the 350 mb level and a potential temperature of 305 K as shown in Fig 8. The split baroclinic structure over Amarillo is supported by the Electra data, but the aircraft measurements indicate a double jet structure which could not be deduced from the sparse radiosonde data.

Potential temperature, wind speed and ozone profiles for the southerly flight are presented in Fig 9. The time scale is discontinuous because the up and downwind sampling periods were eliminated to simulate a continuous flight. Again, the wind speed profile in the stratospheric air is approximately parabolic, while that in the tropospheric air

is more linear. The decrease in potential temperature from 312 to 303 K corresponds to the doming up of the isentropes over the Colorado-New Mexico border. A similar decreasing trend, 320 to 180 ppb, is evident in the ozone maximae. Note that the sudden drops in ozone are correlated with drops in potential temperature and wind speed. These correlations are consistent with air having been forced upward from lower altitudes.

The more sinosoidal oscillations in the ozone profile from 2030 to 2045 GMT are extremely interesting because the correlation between ozone and potential temperature perturbations changes from positive to negative at 2038 GMT. This reversal in the correlation is consistent with transverse waves inclined less steeply than the isentropes and the fact that the mean isentropic gradient is continuous through the zone, while the mean ozone gradient reverses sign at 2038 GMT. The 1.5 min oscillation corresponds to about a 14-15 km wavelength along the flight path.

Similar correlations are evident in portions of the data from the flight of 18 April, when the ethylene sensor was operating. Much more work will be done to analyse these correlations with the objective of identifying these wave modes and determining their momentum and ozone fluxes. The value of the fast responding ozone sensor is certainly evident in these data. For the first time a reliable set of thermal, ozone and inertial navigation data are available

which offers a possibility to identify the wave modes.

Summary

The preliminary evidence presented here from the Electra and commercial flight data obtained during the operation of Project DUSTORM confirms the concept of tropopause folding, as did the radioactivity and aircraft data from Project Springfield. However, we now have much more accurate and faster responding instruments which permit us to resolve not just the large-scale structure, but also the transverse wave modes. The close correspondence between analyses drawn from radiosonde data and the structures observed by the aircraft indicates that the significant potential vorticity boundaries can be positioned to within 60 km from the radiosonde data above. These data also confirm the assumption that ozone rich air is transported into the troposphere with each major cyclonic development, and that this ozone rich air, although diluted by mixing with tropospheric air, can occasionally reach the surface of the earth at values which exceed the EPA standard. The surface deposition pattern is strongly asymmetrical due to the narrowness of the folded structure and the strong deformations in the descending air. Some local regions may be influenced by this ozone rich layer for just 2 or 3 hours, others for 1 or 2 days. More research is necessary to quantify the effects of this ozone source on the surface

ozone chemistry. Because some ozone is required to make more ozone, this source could be significant to the surface ozone problem.

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FIGURE CAPTIONS

Figure 1 Height contours and observed winds at 400 mb, 0000 GMT 19 April 1975. Each barb equals 10 kts; a triangle equals 50 kts. Red overlay includes isotherms of potential temperature in ^{O}K (solid lines), boundaries of folded tropopause (dashed lines) and Electra flight path.

Figure 2 Vertical cross-sections along Electra flight path normal to folded tropopause and jet stream, 0000 GMT 19 April 1975. Isotherms of potential temperature drawn at $2.5^{O}K$ interval. Red overlay includes isotachs at 10 m sec^{-1} interval (solid lines), folded tropopause (dashed lines), and Electra flight levels.

Figure 3 Time profiles of temperature and wind speed measured along 6.4 km Electra flight level across tropopause fold. Red overlay includes profiles of ozone (number mixing ratio) and dew point.

Figure 3b Time profiles of ozone number mixing ratio, and temperature measured along commerical flight path on 18 April 1975. Tropopause level (dashed line) is from conventional tropopause analysis charts.

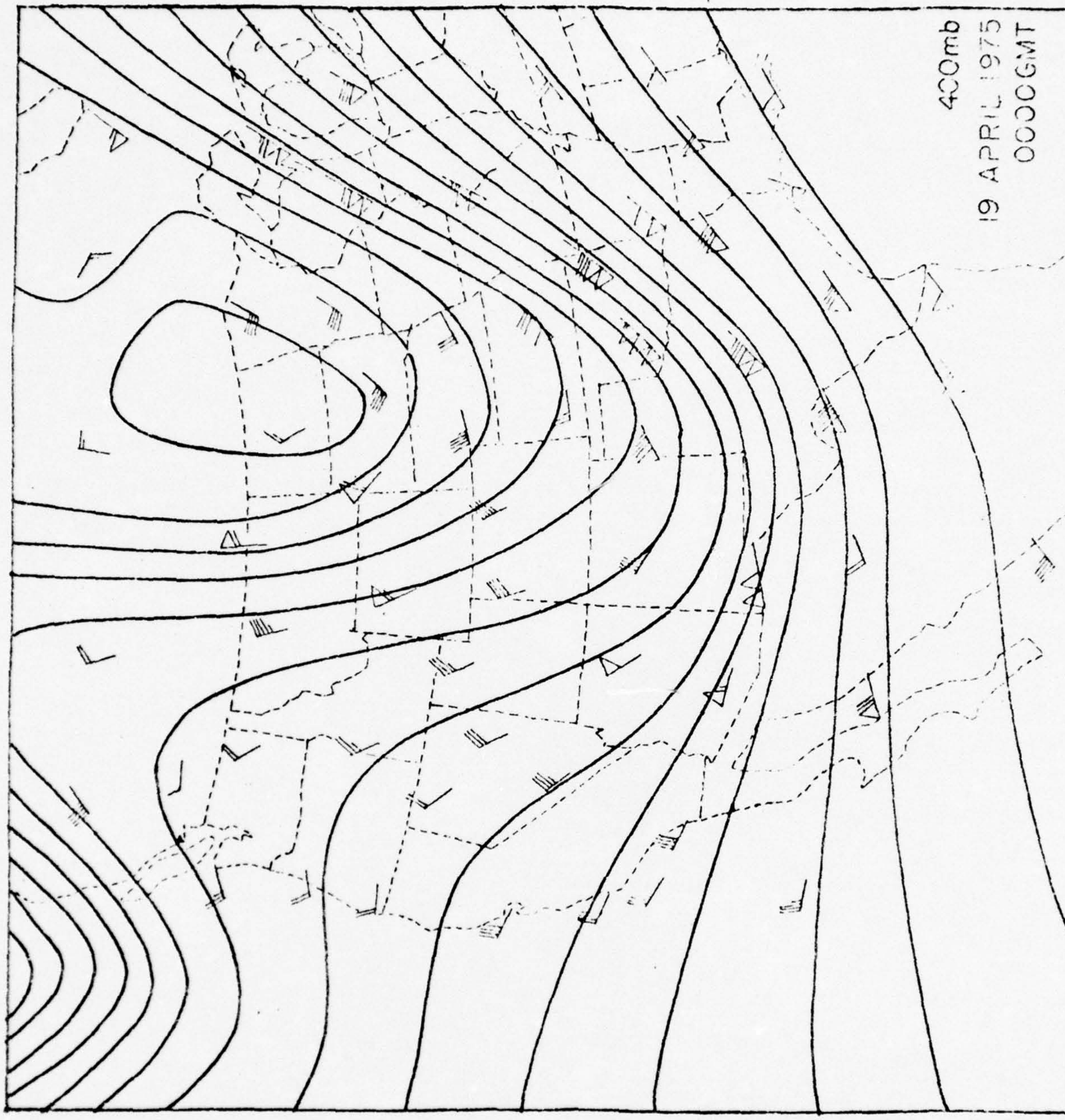
Figure 4 Montgomery stream function contours and observed winds on 320 K isentropic surface, 0000 GMT 27 April 1975. Also, flight path of Electra and commercial aircraft.

Figure 5 Vertical cross-section along Electra flight path, 0000 GMT 27 April 1975. See Fig 2.

Figure 6 Time profiles of potential temperature, wind speed and ozone measured along 7.7 km Electra flight level, from lower stratosphere into troposphere. Ozone number mixing ratio is on the right.

Figure 6b Time profiles of ozone number mixing ratio, wind speed and temperature measured along commercial flight path on 26 April 1975. Tropopause level (dashed line) is from conventional tropopause analysis charts.

Figure 7	Locations of jets and Electra flight paths at 0000 GMT on 26th and 27th of April. Dashed line denotes trajectory of ozone rich air from 26th to 27th.
Figure 8	Vertical cross-section along Electra flight path showing folded tropopause, 0000 GMT 28 April 1975. See Fig 2.
Figure 9	Time profiles of potential temperature, wind speed (black lines) and ozone (red lines) measured along 6.3 km Electra flight level. See Fig 3.



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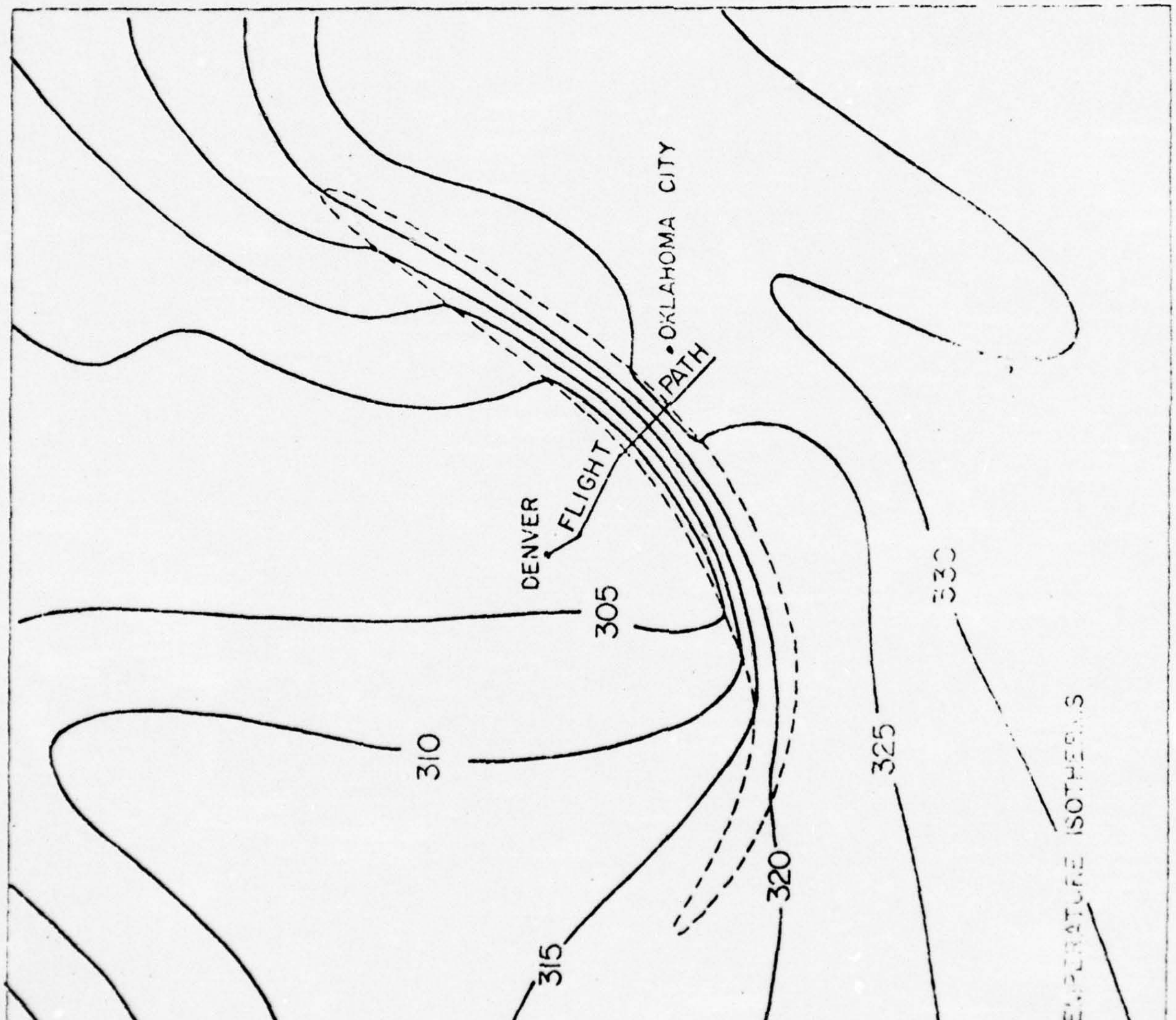
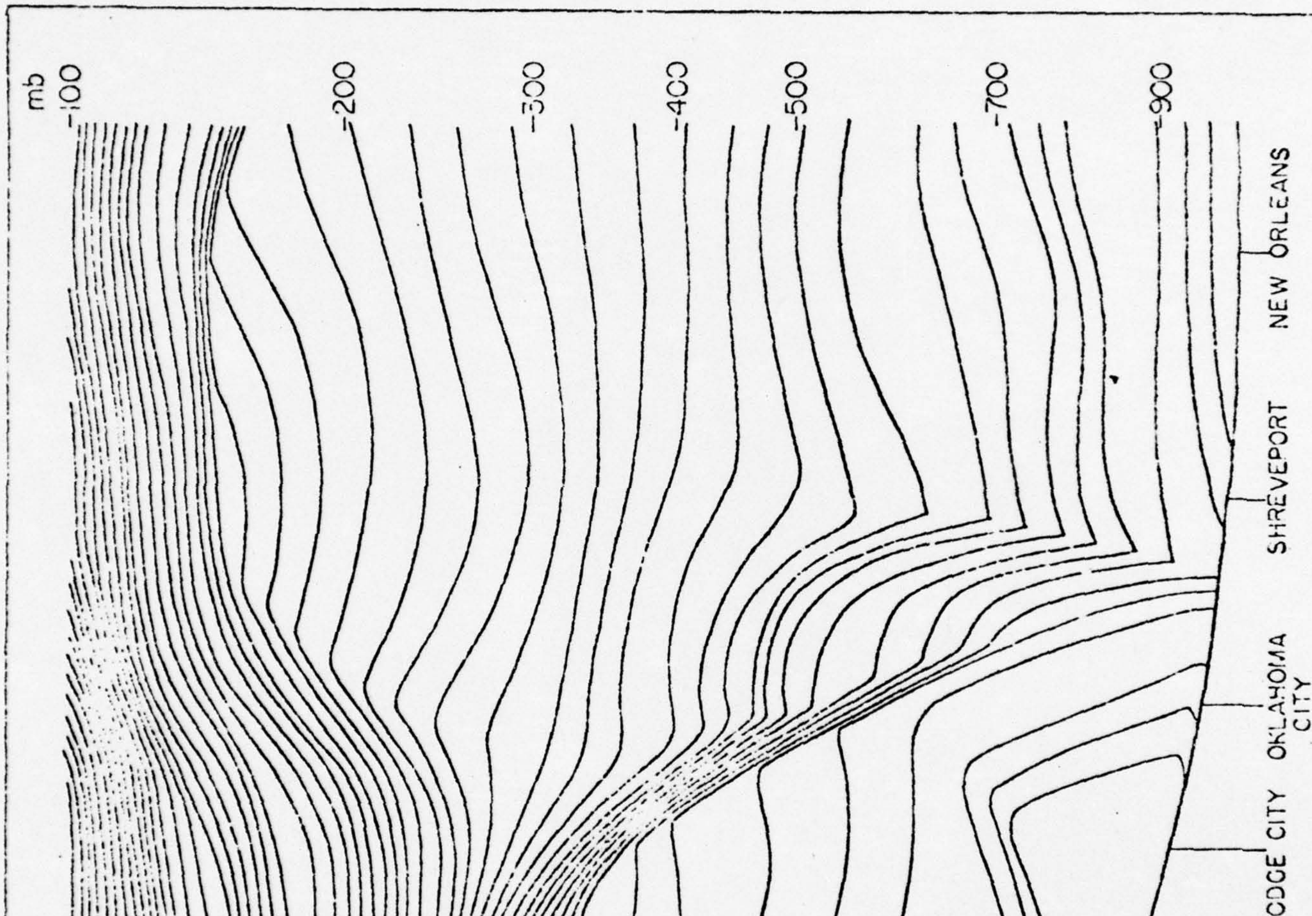


Figure 1 (Red Overlay)



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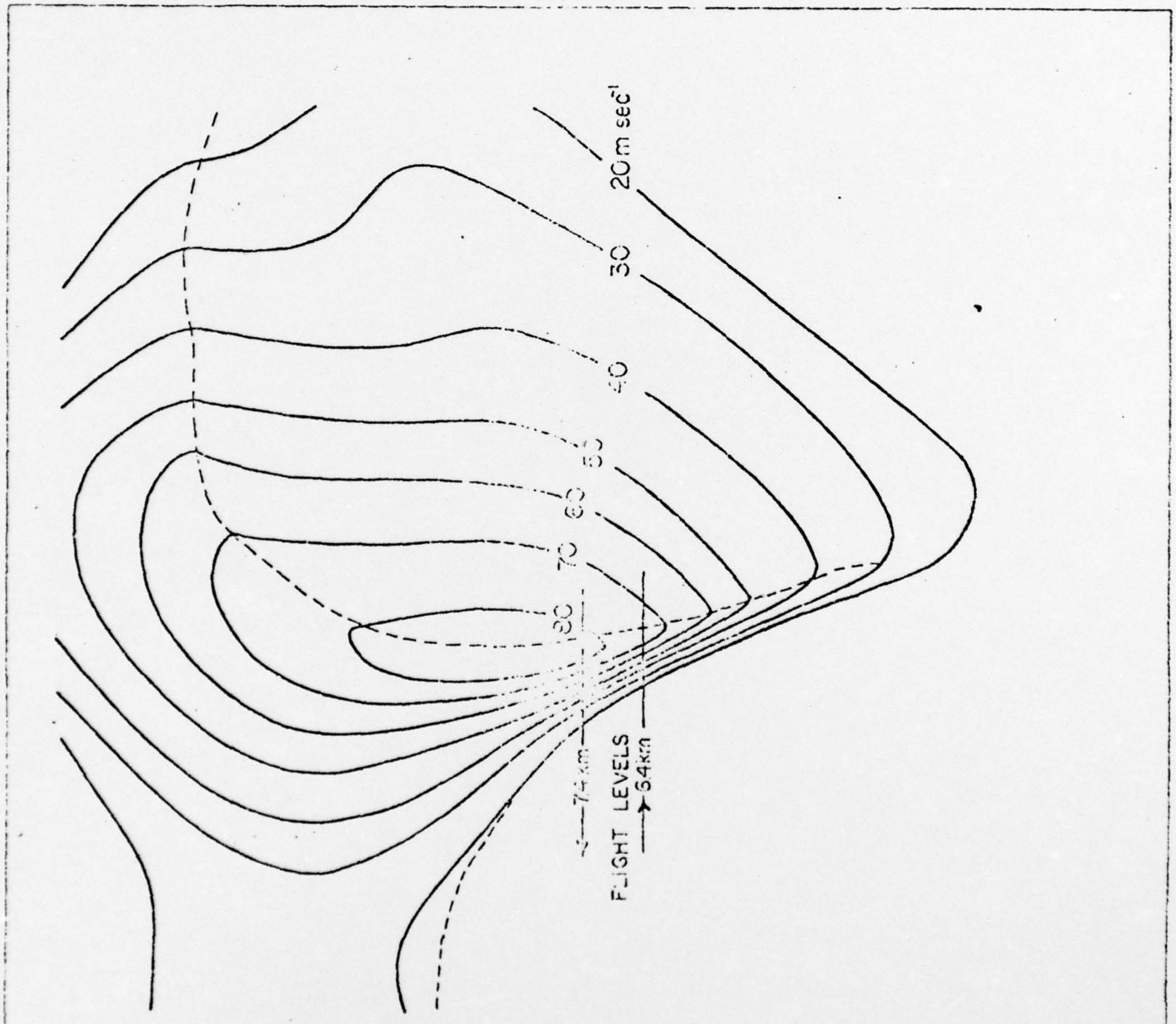

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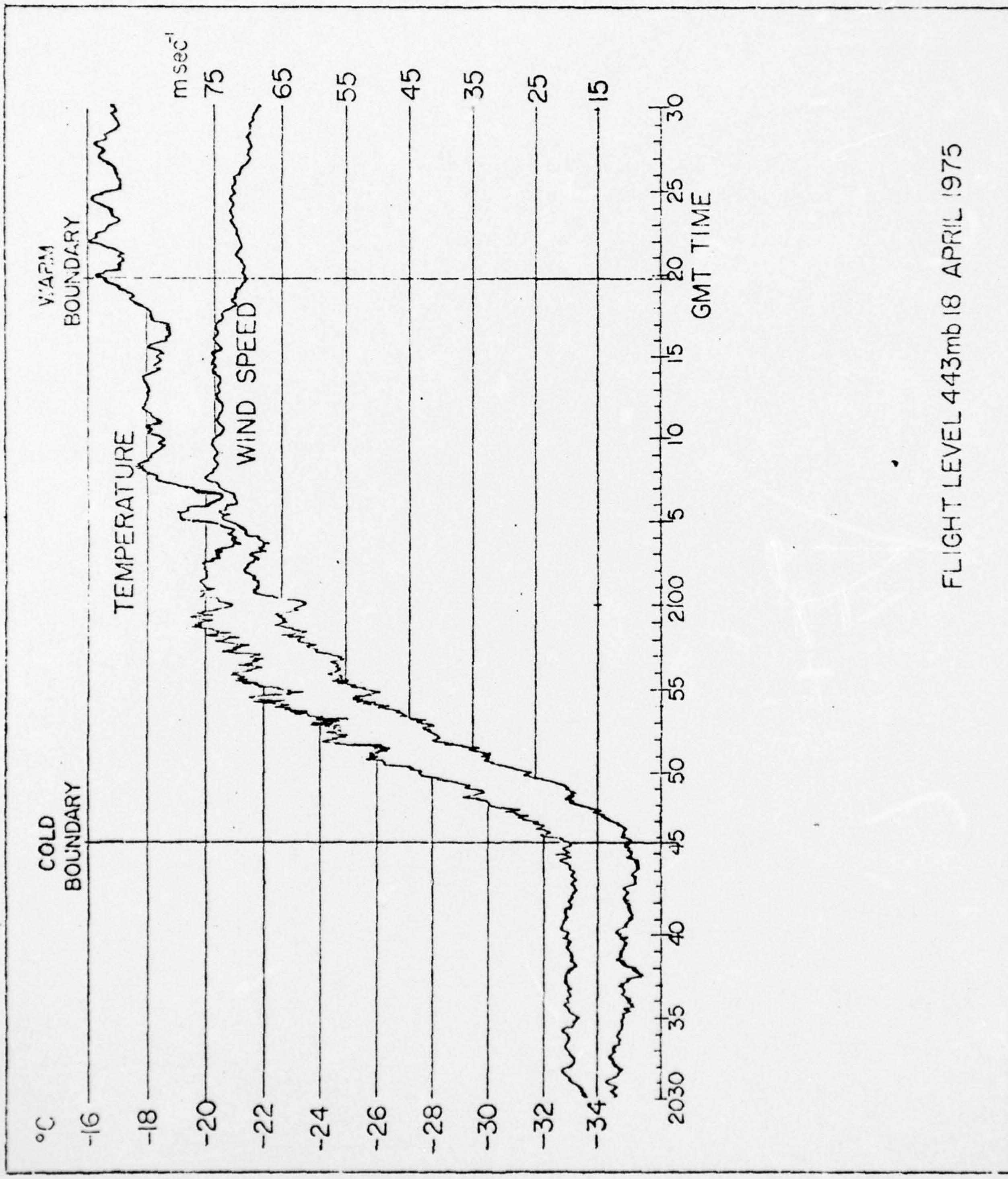

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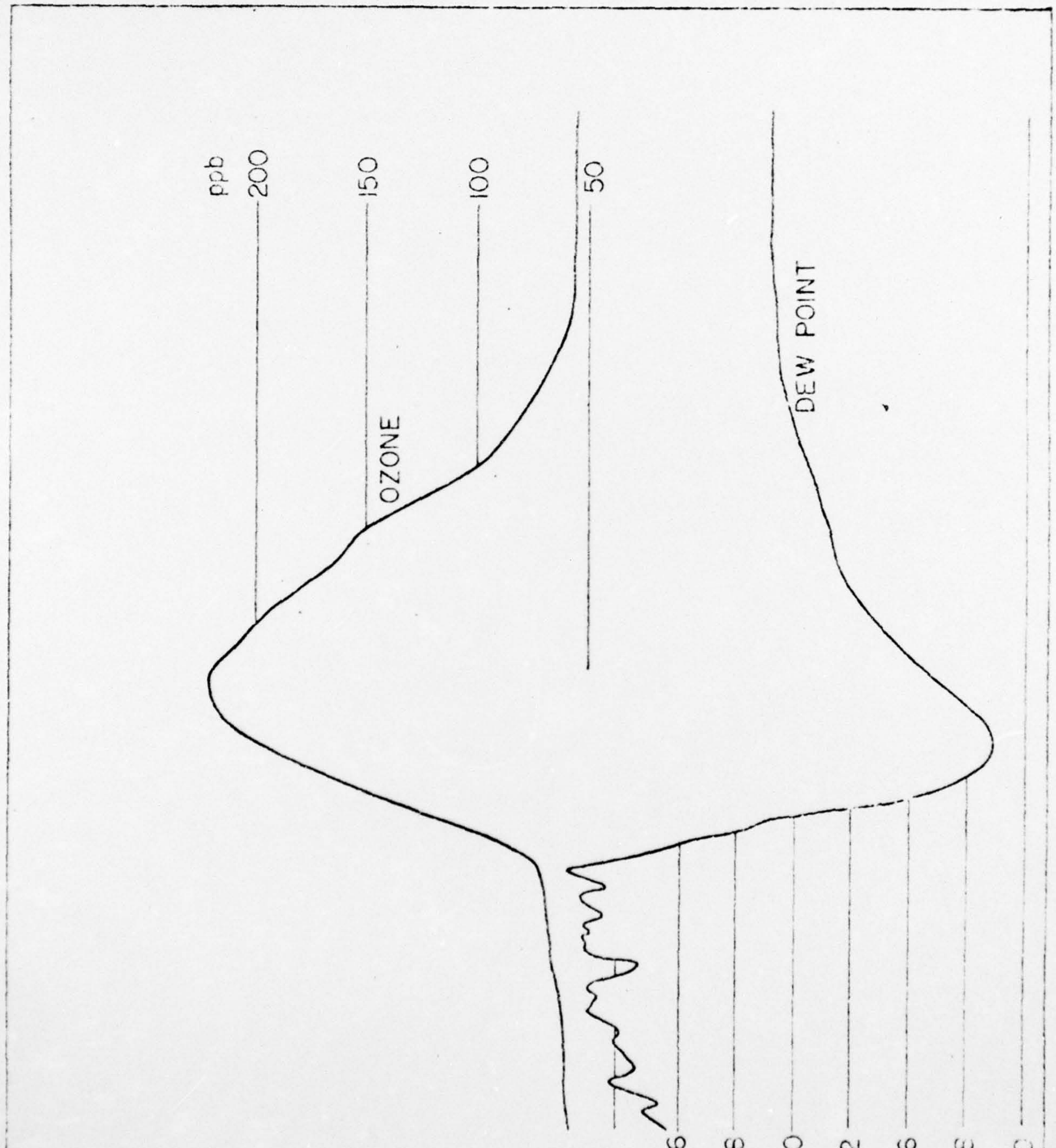

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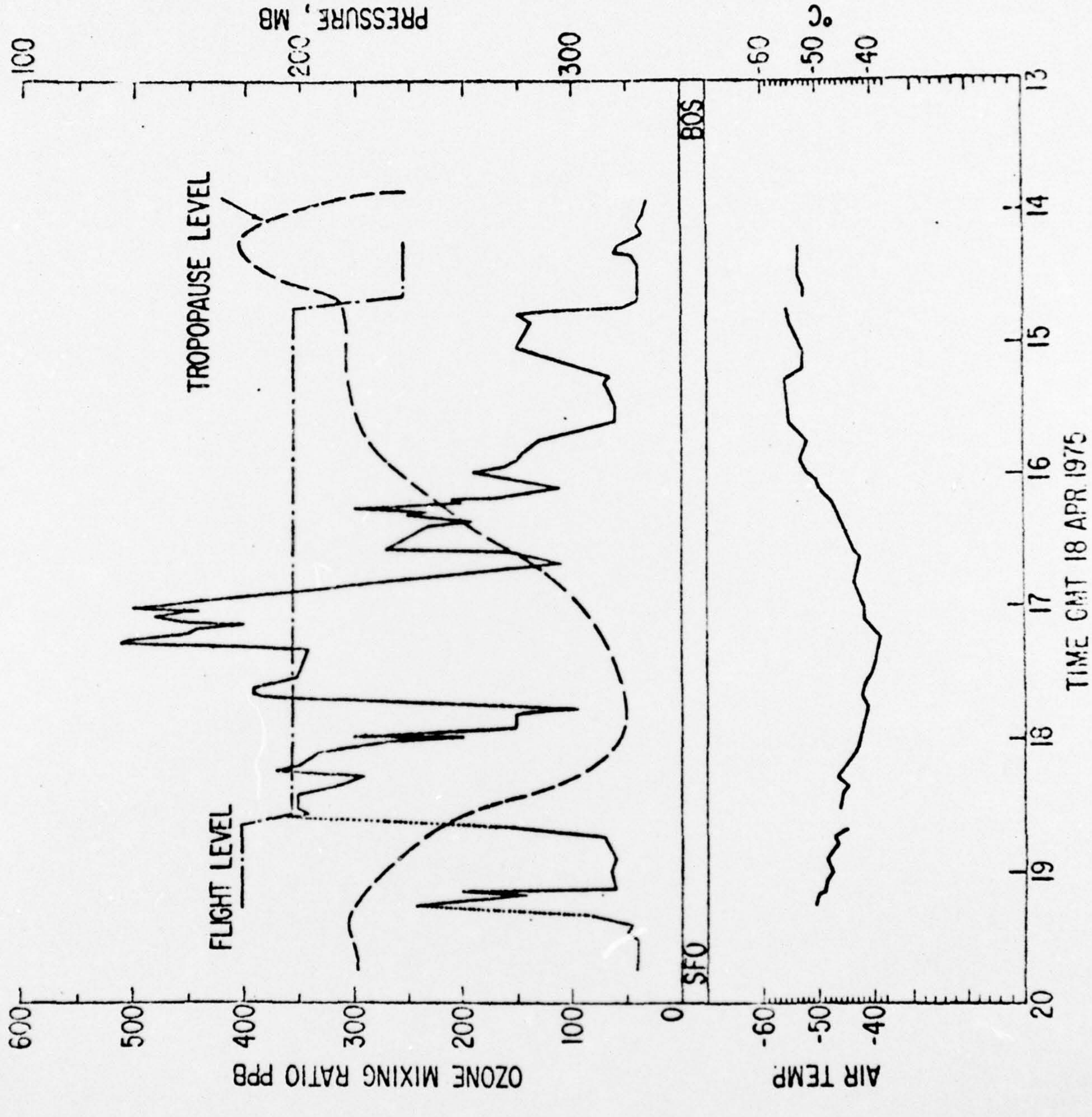

OZONE MIXING RATIO PPB
600
500
400
300
200
100
0
AIR TEMP
-60
-50
-40
PRESSURE, MB
100
200
300
°C
-60
-50
-40
TROPOPAUSE LEVEL
FLIGHT LEVEL
SFO
BOS
20
19
18
17
16
15
14
13
TIME GMT 18 APR 1975

Figure 3b

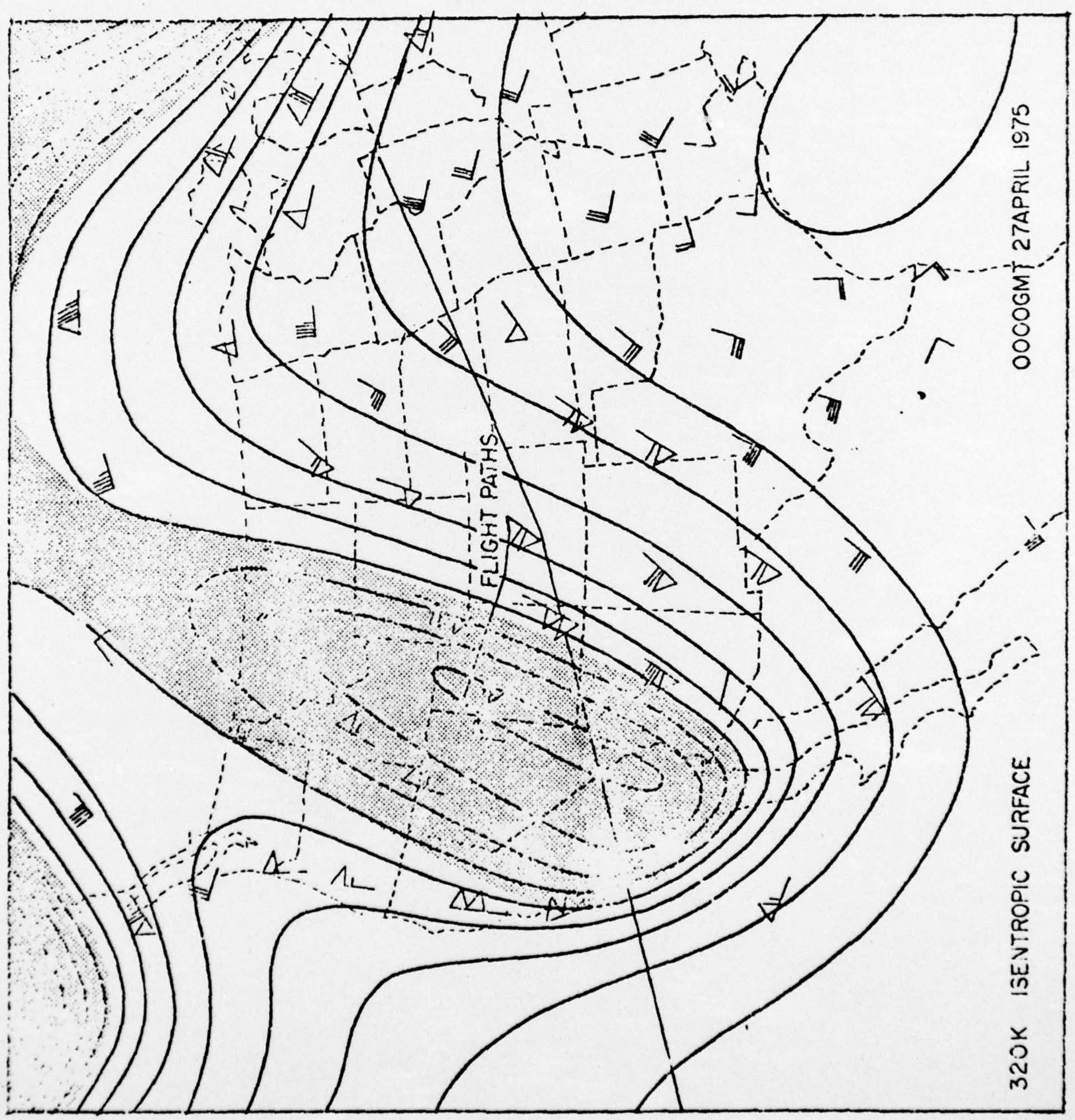

320K ISENTROPIC SURFACE
OOOOGMT 27APRIL 1975
FLIGHT PATHS

Figure 4

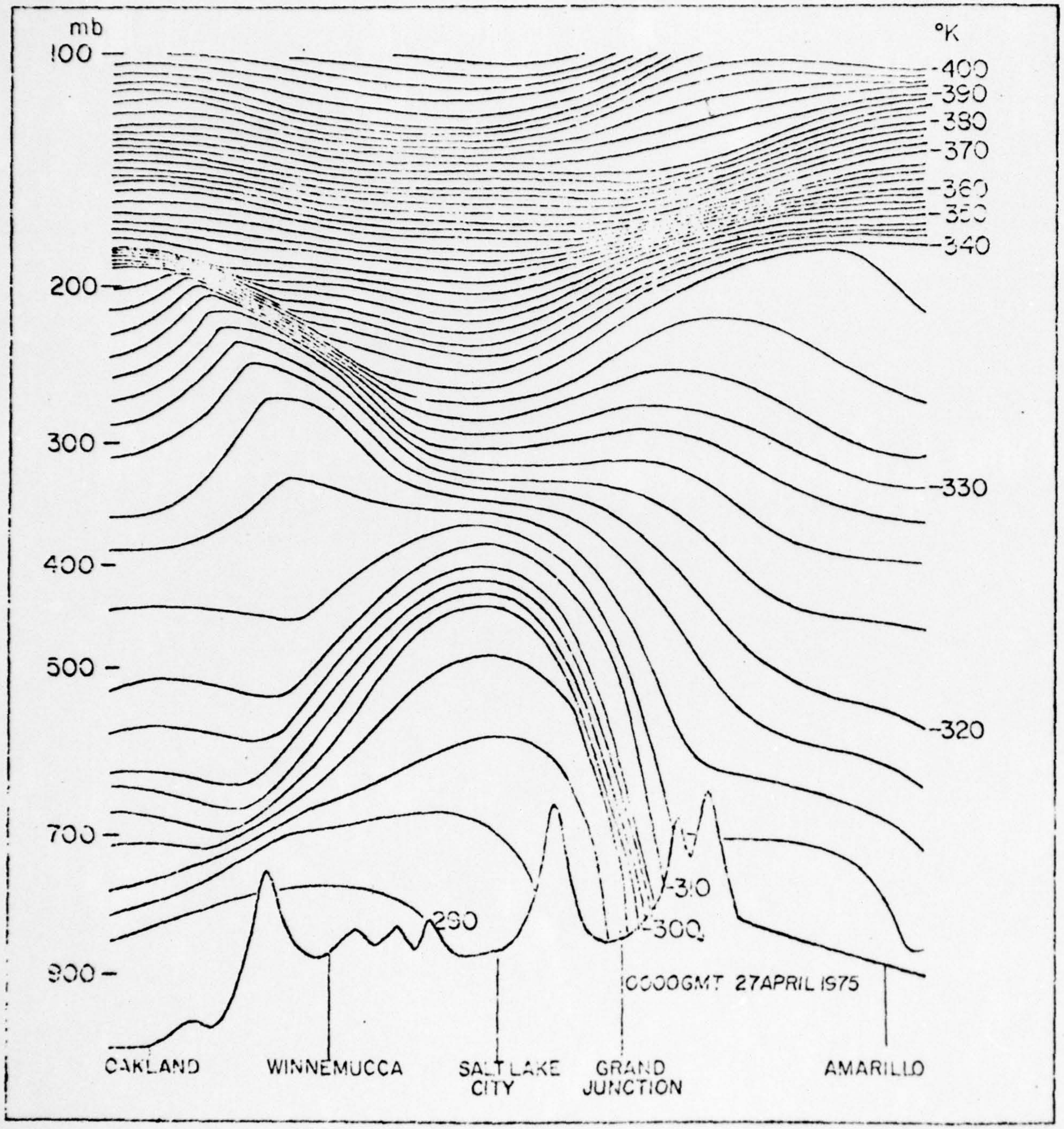


Figure 5 (Black)

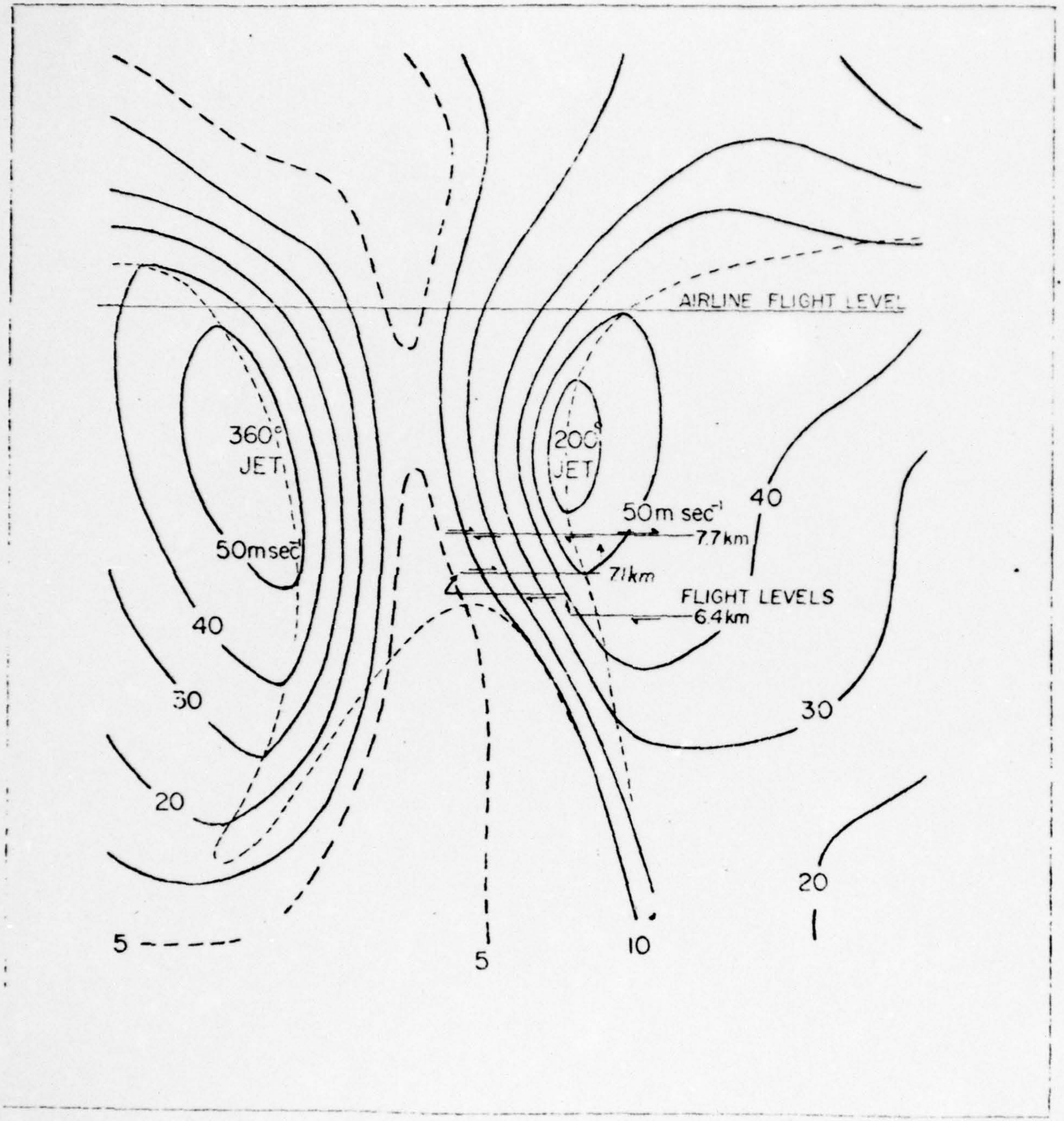


Figure 5 (Red Overlay)

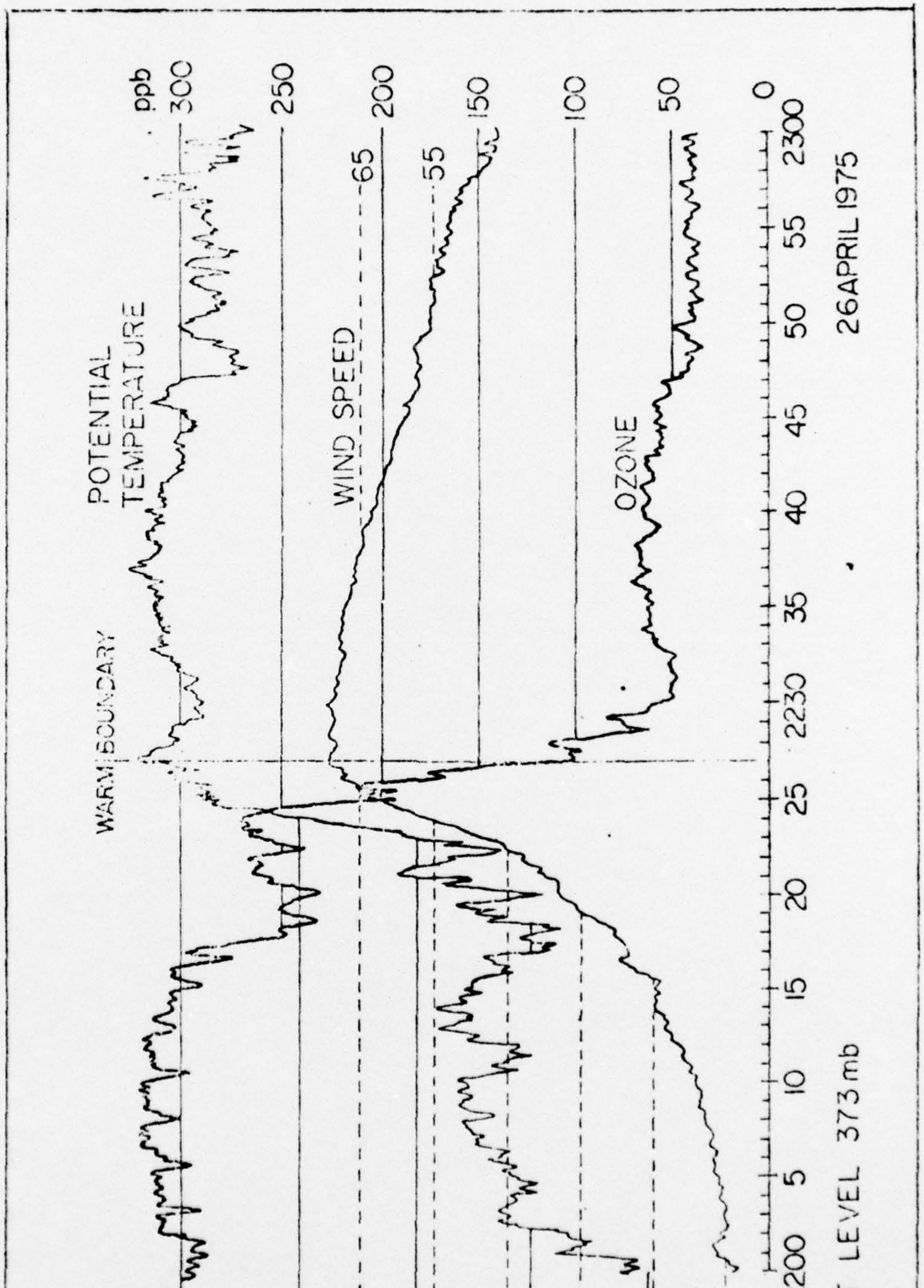
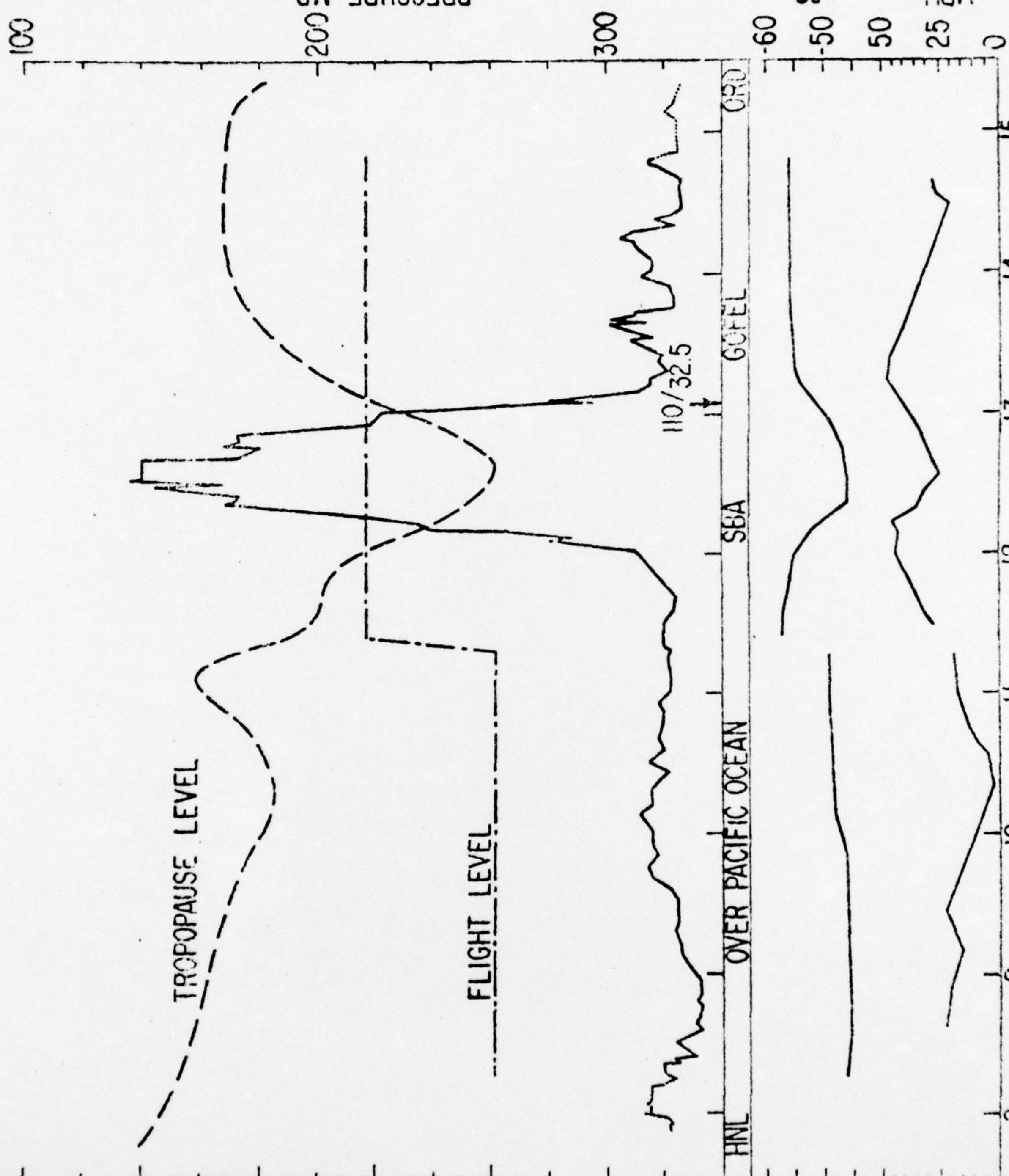

WARM BOUNDARY
POTENTIAL TEMPERATURE
WIND SPEED
OZONE
°K
318
316
314
312
310
m sec⁻¹
65
55
45
35
25
15
ppb
300
250
200
150
100
50
0
65
55
GMT 2200 5 10 15 20 25 2230 35 40 45 50 55 2300
FLIGHT LEVEL 373 mb
26 APRIL 1975

Figure 6



PRESSURE, MB
100
200
300
°C
-60
-50
MPH
50
25
0
TROPOPAUSE LEVEL
FLIGHT LEVEL
HNL
OVER PACIFIC OCEAN
SBA
GOFEL
ORD
110/32.5
600
500
400
300
200
100
0
OZONE MIXING RATIO PPB
AIR TEMP
HORIZ.WIND
8
9
10
11
12
13
14
15
TIME GMT 26 APR 1975

Figure 6b

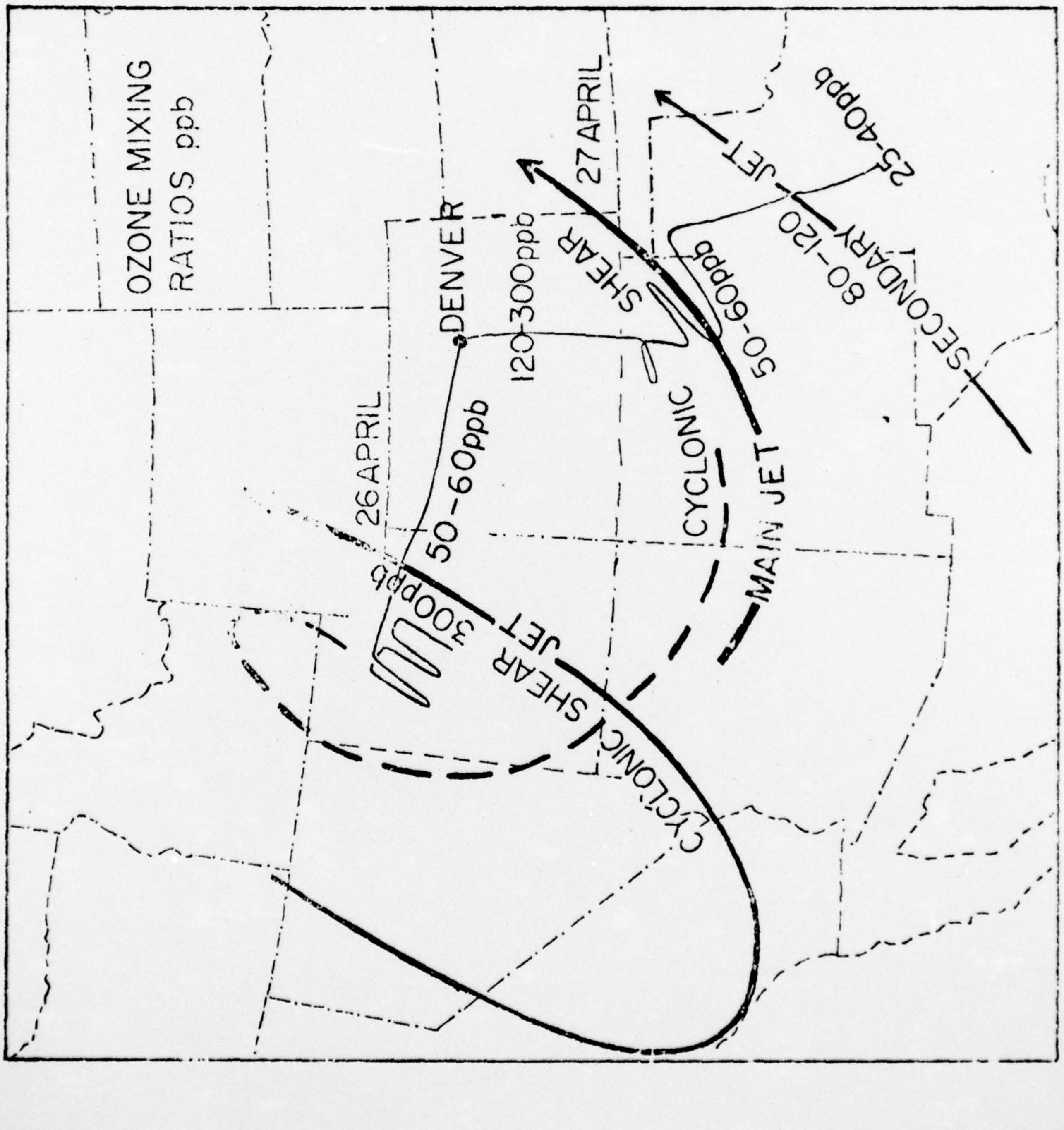

OZONE MIXING
RATIOS ppb
DENVER
26 APRIL
27 APRIL
50-60ppb
120-300ppb
300ppb
CYCLONIC SHEAR JET
SHEAR
CYCLONIC
MAIN JET
50-60ppb
80-120
SECONDARY JET
25-40ppb

Figure 7

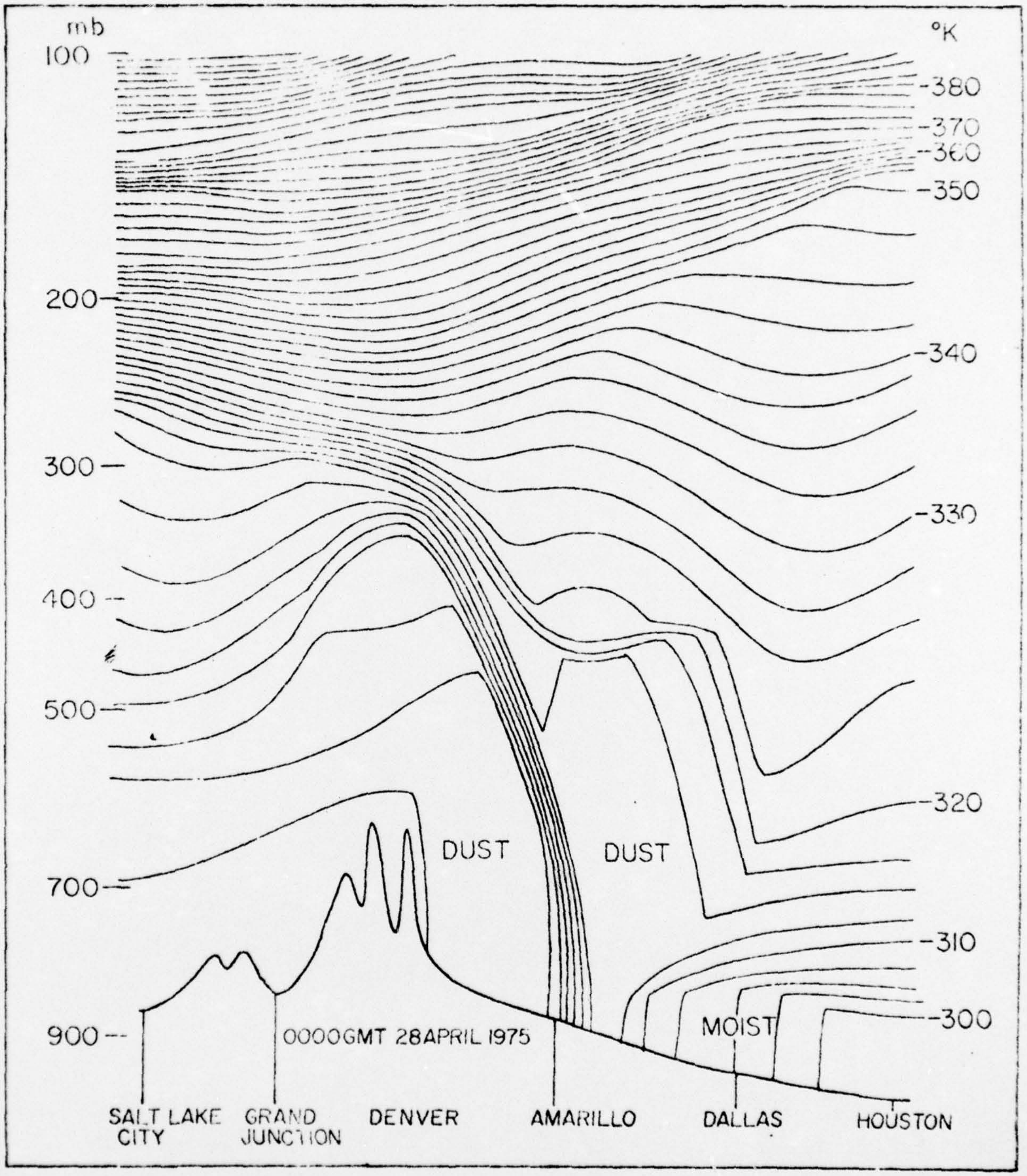


Figure 8 (Black)

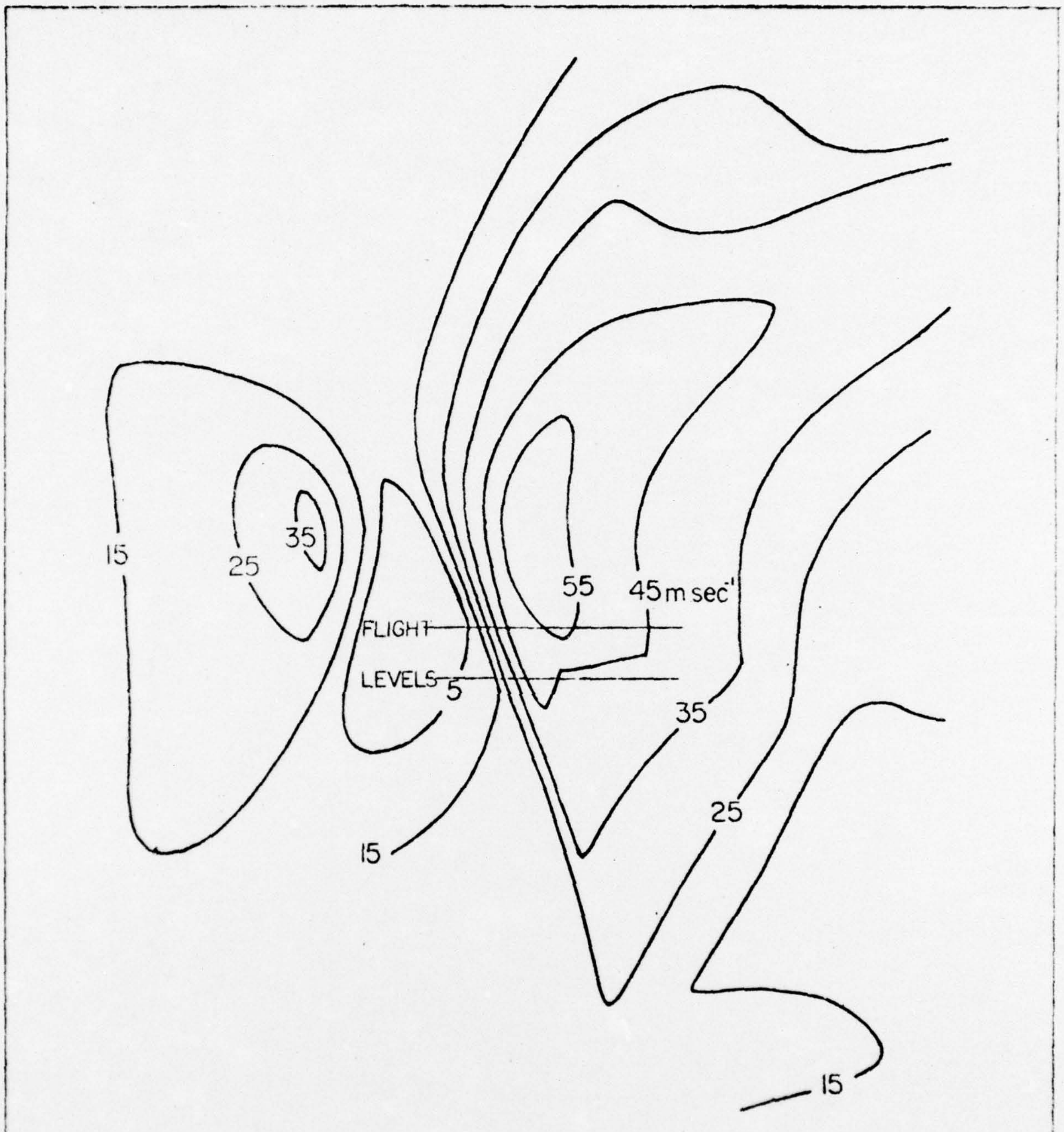


Figure 8 (Red Overlay)

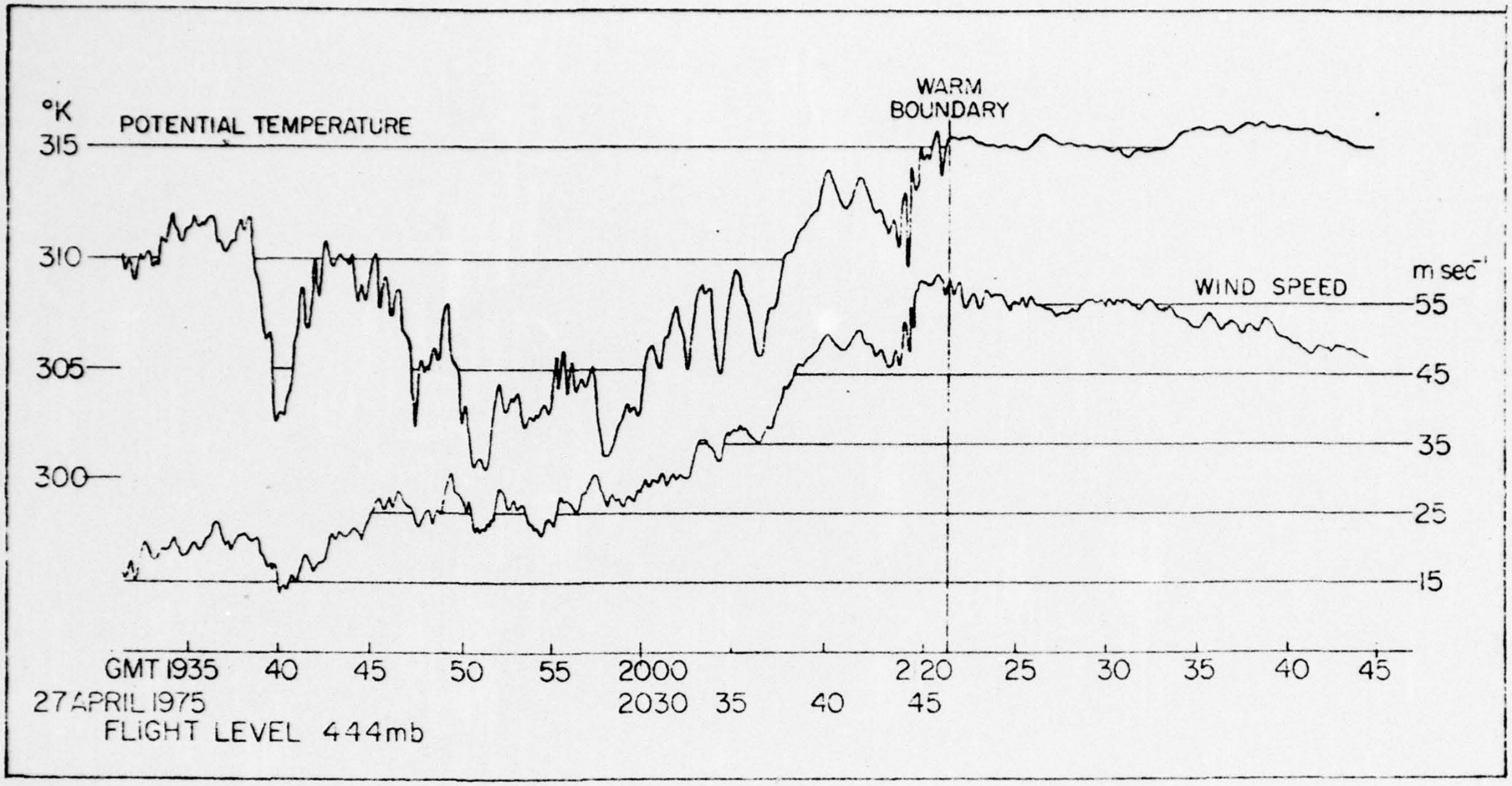


Figure 9 (Black)

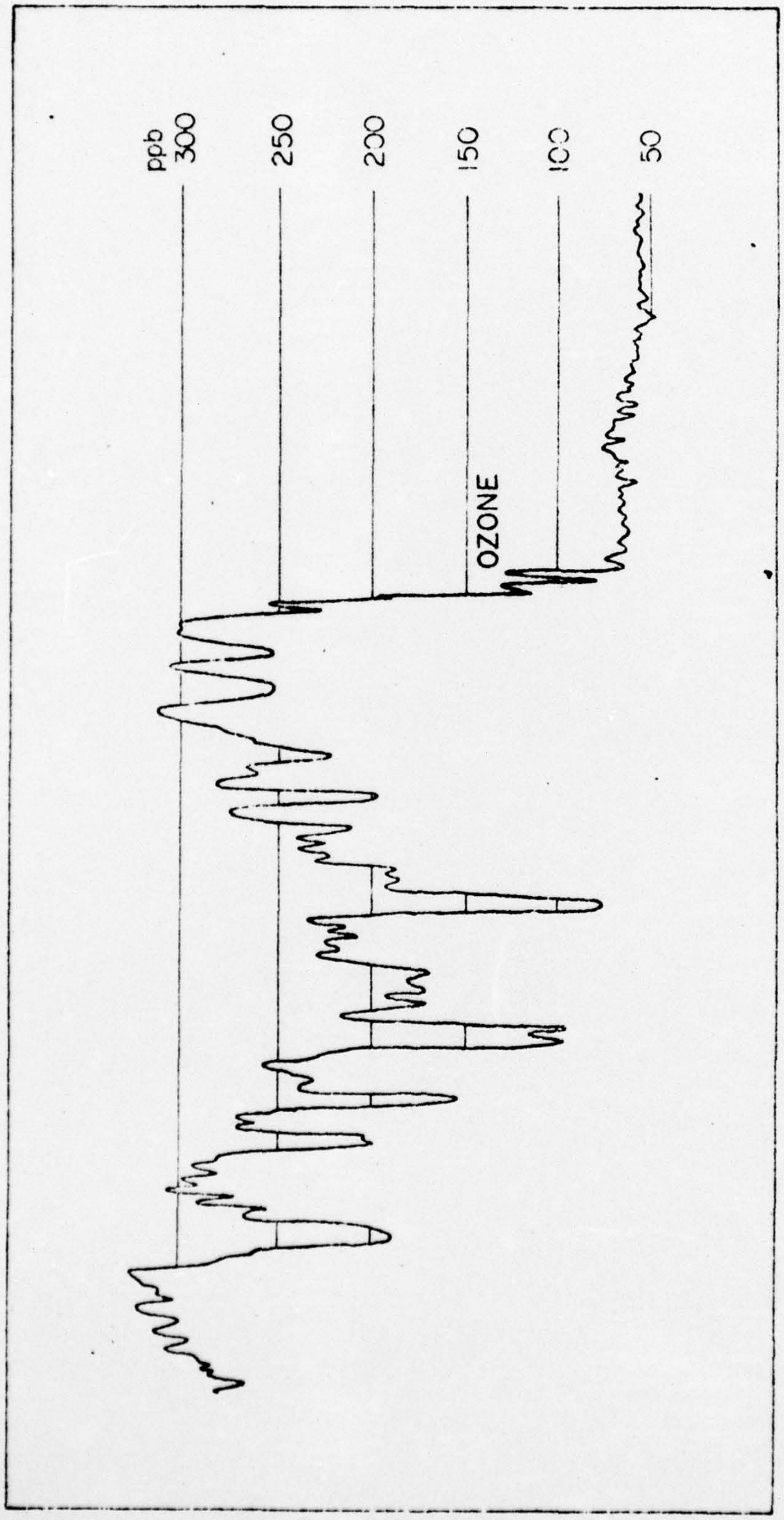


Figure 9 (Red Overlay)